

WHAT IF CHARGED CURRENT EVENTS AT LARGE Q^2 ARE OBSERVED AT HERA?

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Abstract

An excess of events at large Q^2 with a positron in the final state has been observed at HERA which, if confirmed, would be a signal of new physics. It is not clear at present if a signal of comparable rate is also seen in the charged current channel (with an antineutrino in the final state). In this note we analyse the implications of the presence of such a signal in models of new physics based on contact terms, leptoquarks and squarks with R-violating decays. We find that in all cases the most likely possibility is that the charged current signal is absent. As a consequence if this signal is present the resulting indications are very selective. In particular for squarks only charged current events with multi-quark final states are possible with quite definite predictions on the spectrum of supersymmetric particles.

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1 Introduction

As well known by now, both HERA experiments, H1 [1] and ZEUS [2], have reported an excess of events with respect to the Standard Model (SM) expectation in $e^+p \rightarrow e^+X$ at very large and until now unexplored values of $Q^2 \gtrsim 1.5 \times 10^4 \text{ GeV}^2$. The limited statistics and the somewhat imperfect matching of the H1 and ZEUS findings still leave ample margins of doubt on the reality of this new physics indication. However possible explanations invoking either additional contact terms in the effective Lagrangian or a leptoquark of mass $M \sim 200 \text{ GeV}$, presumably an up-type squark (\tilde{q}) decaying with R-parity violation, have been studied in detail [3, 4, 5, 6, 7, 8]. At present it is still not clear if a similar signal is also present in the charged-current (CC) channel, *i.e.* with an antineutrino in the final state. Only the H1 experiment reports 4 possible events in this channel at $Q^2 \gtrsim 1.5 \times 10^4 \text{ GeV}^2$ with 1.77 ± 0.87 expected, too few to reach any definite conclusion, while the ZEUS analysis of the CC channel is still in progress. The presence or absence of a simultaneous CC signal is extremely significant for the identification of the underlying new physics (as it would also be the case for the result of a comparable run with an e^- beam, which however is further away in time). The HERA run presently under way, still with an e^+ beam, will soon tell us more on the reality of the new physics evidence and on whether or not a signal is also present in the CC channel. In view of this, in this note we consider in detail the implications for the CC channel of the various proposed solutions of the HERA effect. We will confirm that in most of the cases the CC signal is not expected to arise. But if it is present at a comparable rate as for the NC signal, the corresponding indications are very selective. A contact term would be practically excluded. If the associated jet is as sharp as in the neutral current (NC) case, suggesting one single final-state quark, then this would point towards a leptoquark of peculiar structure, either with couplings explicitly violating the electroweak $SU(2) \otimes U(1)$ symmetry, or perhaps with couplings to an antineutrino and a charm quark. On the other hand a squark of the charm (\tilde{c}) or top (\tilde{t}) type could lead to a CC signal with multijets in the final state arising from the cascade into quark plus gaugino, the latter decaying via R-violating couplings to a neutrino plus two quarks. Well specified small regions of the parameter space should be selected in order to produce a CC signal with the required features. The relevant distributions for this type of decay will be studied in some detail. In the following we will first study the case of contact terms, then we will discuss leptoquarks in general and finally we will deal with the squarks with R-violating interactions.

2 Contact Terms

From the present NC data one cannot exclude a non resonant solution, although the H1 data do indeed favour a leptoquark resonance. Thus at the moment one can obtain a reasonable, although not very good, fit of the available distributions in the NC channel in terms of vector contact terms of the general form

$$\Delta L = \frac{4\pi\eta_{ij}}{(\Lambda_{ij}^\eta)^2} \bar{e}_i \gamma^\mu e_i \bar{q}_j \gamma_\mu q_j \quad (1)$$

with $i, j = L, R$ and η a \pm sign. Strong limits on these contact terms are provided by LEP [9, 10], Tevatron [11] and atomic parity violation (APV) experiments [12, 13]. But for example a parity conserving combination $(\bar{e}_L \gamma^\mu e_L)(\bar{u}_R \gamma_\mu u_R) + (\bar{e}_R \gamma^\mu e_R)(\bar{u}_L \gamma_\mu u_L)$ with $\Lambda_{LR}^+ = \Lambda_{RL}^+ \sim 3$ TeV leads to an acceptable fit to the HERA data and is compatible with the existing limits [3, 6, 7]. For this contact term, even in the limit of $SU(2)$ symmetry, there is no need for an associated CC signal, because the current $\bar{e}_L \gamma^\mu e_L$ could be part of a singlet $\bar{e}_L \gamma^\mu e_L + \bar{\nu}_L \gamma^\mu \nu_L$. We note that for contact terms it is natural to assume the validity of the $SU(2) \otimes U(1)$ symmetry, because they are associated with physics at a large energy scale.

Suppose now that there is a CC signal of comparable rate as the NC one. In the $SU(2) \otimes U(1)$ limit, restricting us to family diagonal quark currents in order to minimise problems with the occurrence of flavour changing neutral currents, the only possible vector contact term with valence quarks (and no Cabibbo suppression) is of the form

$$\Delta L_{CC} = \frac{4\pi\eta}{\Lambda_\eta^2} \bar{e}_L \gamma^\mu \nu_L \bar{u}_L \gamma_\mu d'_L + \text{h.c.} \quad (2)$$

i.e. the product of two isovector currents. Here d'_L is the left-handed d-quark current eigenstate, related to the mass eigenstate by the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

It is simple to see that such terms cannot have a sufficient magnitude. On the one hand the rate for events with antineutrinos in the final state would be modified by the presence of the contact term of the form in eq. (2) by an amount that can easily be estimated because the chiral structure of the additional term is the same as in the SM. Neglecting the charm-quark contribution we have

$$\frac{d\sigma}{dQ^2}(\Lambda) = \frac{d\sigma_{SM}}{dQ^2} \left[1 - \frac{2\eta \sin^2 \theta_W (Q^2 + M_W^2)}{\alpha \Lambda^2} \right]^2. \quad (3)$$

Inserting the values of the electromagnetic coupling α , the weak mixing angle θ_W and the W mass, for $Q^2 = 15000 \text{ GeV}^2$ we find

$$\frac{d\sigma}{dQ^2}(\Lambda) = \frac{d\sigma_{SM}}{dQ^2} \left[1 - \eta (1.1 \text{ TeV}/\Lambda)^2 \right]^2 \quad (4)$$

Thus values of Λ in the range between 1 and 1.5 TeV and $\eta = -1$ would be required to produce a sizeable excess.

On the other hand, the scale Λ associated with this operator is strongly constrained by at least two experimental facts: lepton-hadron universality of weak charged currents and electron-muon universality in charged-pion decays. Consider the strength of the four fermion interaction responsible for muon decay and compare it to that of the similar term with the muon current replaced by the $u \rightarrow d'$ current. The only room for a new interaction as in eq. (2) is within the allowed discrepancy from unitarity of the CKM matrix. From the experimental values [14]:

$$|V_{ud}| = 0.9736 \pm 0.0010, \quad |V_{us}| = 0.2205 \pm 0.0018, \quad |V_{ub}| = 0.0033 \pm 0.0009 \quad (5)$$

one finds

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9965 \pm 0.0022 \quad (6)$$

As a consequence, at 1.64σ , one obtains the constraint

$$0.9929 < 1 - \frac{2\sqrt{2}\pi\eta}{G_F\Lambda_\eta^2} < 1.0001 \quad (7)$$

Thus at 90% CL one finds that $\Lambda_+ > 10$ TeV and $\Lambda_- > 87$ TeV.

We now consider $e-\mu$ universality in charged pion decay. We assume that there is a contact term for electron but not for muon currents. Then the ratio $R = \Gamma(\pi^- \rightarrow e\bar{\nu})/\Gamma(\pi^- \rightarrow \mu\bar{\nu})$ would deviate from its SM value by

$$R = R_{SM}(1 - \frac{2\sqrt{2}\pi\eta}{G_F\Lambda_\eta^2}) \quad (8)$$

According to ref. [15] the present experimental value of R_{exp}/R_{SM} is given by:

$$R_{exp}/R_{SM} = 0.9966 \pm 0.0030 . \quad (9)$$

As a consequence, at 1.64σ we find

$$0.9917 < 1 - \frac{2\sqrt{2}\pi\eta}{G_F\Lambda_\eta^2} < 1.0015 . \quad (10)$$

This leads to $\Lambda_+ > 10$ TeV and $\Lambda_- > 23$ TeV at 90% CL.

We conclude that vector contact terms of this type could at most lead to a CC signal below the percent level with respect to the NC one. This statement remains true even if we relax the $SU(2) \otimes U(1)$ symmetry. For example, if we impose that the axial hadronic current vanishes, in order to evade the charged-pion constraint, the universality bound is still valid for the vector hadronic current with respect to the muon vector current. Similarly, trying to restore $e-\mu$ universality by also allowing a corresponding contact term with the electron current replaced by a muon current with exactly the same coupling would also fail. First of all there are strong limits from the precisely measured ratio R_ν of NC to CC rates in ν_μ induced deep inelastic reactions [14]. Secondly, the limit from the comparison with muon decay remains valid. Moreover we cannot also introduce a contact term which contributes to muon decay, because the determination of G_F would be affected and precision tests of the SM practically exclude that. Furthermore, very stringent limits from $e^+e^- \rightarrow \mu^+\mu^-$ have been set by OPAL [9].

The possible scalar or tensor currents arising from an $SU(2) \otimes U(1)$ invariant theory which can contribute to valence-parton CC processes are

$$\mathcal{L} = \frac{4\pi}{\Lambda_S^2}(\bar{e}_R\nu_L)(\bar{u}_Rd_L) + \frac{4\pi}{\Lambda_{S'}^2}(\bar{e}_R\nu_L)(\bar{u}_Ld_R) + \frac{4\pi}{\Lambda_T^2}(\bar{e}_R\sigma^{\mu\nu}\nu_L)(\bar{u}_R\sigma_{\mu\nu}d_L) , \quad (11)$$

while the operator $(\bar{e}_R\sigma^{\mu\nu}\nu_L)(\bar{u}_L\sigma_{\mu\nu}d_R)$ identically vanishes. The scalar interactions are strongly limited by $e-\mu$ universality in pion decays [16],

$$\Lambda_{S,S'} > 500 \text{ TeV} , \quad (12)$$

because they do not lead to electron-helicity suppression, in contrast with the SM case. Even introducing a muon counterpart to the electron contact term could not help in this case barring an unbelievable level of fine tuning. The tensor interaction can be dressed into a scalar interaction of effective strength [17]

$$\frac{1}{\Lambda_{S\,eff}^2} \simeq -\frac{\alpha}{\pi} \log\left(\frac{\Lambda_T^2}{M_W^2}\right) \frac{1}{\Lambda_T^2}, \quad (13)$$

with the exchange of a photon between the electron and the quark fields. Then lepton universality in pion decays sets the limit

$$\Lambda_T > 90 \text{ TeV}. \quad (14)$$

Considering now also CC processes involving sea quarks, we can introduce a contact term for second generation quarks

$$\Delta L_{CC} = \frac{4\pi\eta}{\Lambda_\eta^{(2)2}} (\bar{e}_L \gamma^\mu \nu_L) (\bar{c}_L \gamma_\mu s'_L) + \text{h.c.} \quad (15)$$

Clearly since the strange sea in the proton is small one needs relatively small values of Λ in order to produce a sufficiently large effect. A detailed study shows that one needs $\Lambda \sim 0.8 - 1 \text{ TeV}$ with $\eta = -1$ in order to obtain an increase by a factor of two with respect to the SM at $Q^2 = 15000 \text{ GeV}^2$. Contact terms with $\eta = 1$ give negative interference at HERA and one would be forced to take Λ very small in order to take advantage of the contact term squared. However such a term would lead to a disagreement with the data at low Q^2 .

Bounds on the scales $\Lambda_\eta^{(2)}$ can be derived from lepton universality in D decays [14]

$$R_{e/\mu}^D \equiv \frac{\Gamma(D^0 \rightarrow K^- e^+ \nu)}{1.03 \times \Gamma(D^0 \rightarrow K^- \mu^+ \nu)} = 1.09 \pm 0.09. \quad (16)$$

Here the factor 1.03 takes into account the phase-space suppression of the muon channel. The operator in eq. (15) predicts a deviation from universality

$$R_{e/\mu}^D = 1 - \frac{2\sqrt{2}\pi\eta}{G_F \Lambda_\eta^{(2)2}}, \quad (17)$$

and it is therefore constrained by eq. (16) to satisfy

$$\Lambda_+^{(2)} > 3.6 \text{ TeV} \text{ at } 90\% \text{ CL}, \quad (18)$$

$$\Lambda_-^{(2)} > 1.8 \text{ TeV} \text{ at } 90\% \text{ CL}. \quad (19)$$

Bounds that do not rely on $e - \mu$ universality can be obtained from the unitarity of the CKM matrix. One can compare $|V_{cs}|$ obtained from unitarity by $|V_{cs}| = \sqrt{1 - |V_{us}|^2 - |V_{ts}|^2}$ with the value directly measured from $D \rightarrow K e \nu$, which is affected by the contact term in eq. (15). Using $|V_{ts}| = 0.040 \pm 0.004$ and $|V_{us}| = 0.2205 \pm 0.0018$ [14], we have $|V_{cs}| = \sqrt{1 - |V_{us}|^2 - |V_{ts}|^2} = 0.9746 \pm 0.0004$. This is to be compared with $|V_{cs}| = 1.01 \pm 0.18$ from $D \rightarrow K e \nu$ [14]. As a result we find

$$\Lambda_+^{(2)} > 1.2 \text{ TeV} \text{ at } 90\% \text{ CL}, \quad (20)$$

$$\Lambda_-^{(2)} > 1.1 \text{ TeV at 90\% CL.} \quad (21)$$

If we introduced an $e - \mu$ symmetric combination of contact terms a comparison between the value of $|V_{cd}|$ [14] extracted from charm production off d -valence quarks in (muon) neutrino-scattering experiments and the value of $|V_{cd}|$ extracted from unitarity plus knowledge of $|V_{ud}|$ and $|V_{td}|$ [14] would set on the common coupling the limits

$$\Lambda_+^{(2)} > 1.7 \text{ TeV at 90\% CL,} \quad (22)$$

$$\Lambda_-^{(2)} > 1.9 \text{ TeV at 90\% CL.} \quad (23)$$

These limits are at the level of the present sensitivity of LEP2 experiments [10], but should be improved after the next run.

Scalar contact terms involving second-generation quarks are constrained by leptonic decays of K^+ , K^0 , and D^0 and cannot give a significant contribution to CC events at HERA.

In conclusion it appears very difficult to accomodate a CC signal at HERA in the framework of contact terms.

3 Leptoquarks

Let us now consider a scalar leptoquark resonance that is coupled both to e^+d and to $\bar{\nu}u$ so that it can generate both NC and CC events from valence (note that e^+u has charge $+5/3$ and cannot go into $\bar{\nu}q$). A vector leptoquark has a much larger cross section at the Tevatron than a scalar leptoquark [18], and current [19] or upcoming limits should be able to rule out this possibility. Assuming that the symmetry under $SU(2) \otimes U(1)$ is conserved, the virtual leptoquark exchange gives a CC contribution to the low-energy effective Lagrangian of the form

$$\mathcal{L} = \frac{\lambda_u \lambda_d}{M^2} (\bar{e}_R d_L) (\bar{u}_R \nu_L) + h.c. \quad (24)$$

Here λ_u and λ_d are the (real) couplings of a leptoquark with mass M to the $\bar{\nu}_L u_R$ and $\bar{e}_R d_L$ currents, respectively. This interaction corresponds to the transition $e_L^+ d_L \rightarrow \bar{\nu}_R u_R$ which has $T = -1/2$ both in the initial and final states. At low energies, the leptoquark exchange induces a contribution to $\pi \rightarrow e\bar{\nu}$ which is not helicity suppressed. After Fierz rearranging eq. (24), we can translate the limit in eq. (12) into an upper bound on the leptoquark branching ratio into neutrinos, $BR(LQ \rightarrow \bar{\nu}u) \simeq \frac{\lambda_u^2}{\lambda_d^2} < 5 \times 10^{-6}$ for $M \sim 200 \text{ GeV}$ and $\lambda_d \sim 0.04$ [3]. This clearly excludes any observable CC signal, if the scalar leptoquark produced from valence quarks has gauge-invariant couplings.

An alternative is to break $SU(2) \otimes U(1)$ and assume that the leptoquark exchange induces an effective interaction of the form

$$\mathcal{L} = \frac{\lambda_u \lambda_d}{M^2} (\bar{e}_L d_R) (\bar{u}_R \nu_L) + h.c. \quad (25)$$

Note that in the transition $e_R^+ d_R \rightarrow \bar{\nu}_R u_R$ the initial state has $T = +1/2$ while the final state has $T = -1/2$. In this case the low energy effective interaction gives a contribution to $\pi \rightarrow e\bar{\nu}$

which is helicity suppressed and so could be acceptable. In fact by Fierz rearrangement we have

$$\mathcal{L} = -\frac{\lambda_u \lambda_d}{2 M^2} (\bar{e}_L \gamma^\mu \bar{\nu}_L) (\bar{u}_R \gamma_\mu d_R) + h.c. , \quad (26)$$

where the minus sign comes from the anticommutative properties of the fermionic fields. The limits discussed in eqs. (8)–(10) give

$$|\lambda_u \lambda_d| < 1 \times 10^{-2} \left(\frac{M}{200 \text{ GeV}} \right)^2 \quad \text{if } \lambda_u \lambda_d > 0 , \quad (27)$$

$$|\lambda_u \lambda_d| < 2 \times 10^{-3} \left(\frac{M}{200 \text{ GeV}} \right)^2 \quad \text{if } \lambda_u \lambda_d < 0 . \quad (28)$$

We recall that the observed rate of the NC events at HERA requires [3] $|\lambda_d| \simeq 4 \times 10^{-2} / \sqrt{1 - \mathcal{B}_{\nu u}}$, where $\mathcal{B}_{\nu u} \equiv BR(LQ \rightarrow \bar{\nu} u) = (1 + \lambda_d^2 / \lambda_u^2)^{-1}$. Equations (27) and (28) allow $\mathcal{B}_{\nu u}$ values as large as 73% if λ_u and λ_d have the same sign and up to 38% if they have opposite sign.

It is interesting to speculate on how the leptoquark couplings could violate gauge invariance. Since $SU(2) \otimes U(1)$ is broken only by the Higgs vacuum expectation value (VEV), we have to assume that the leptoquark couples to the quark-lepton current through some higher-dimensional operator. Indeed, the dimension-five interactions

$$\mathcal{L} = \frac{\hat{\lambda}_u}{\mathcal{M}} \Phi \bar{u}_R H^T (-i\sigma_2) \ell_L + \frac{\hat{\lambda}_d}{\mathcal{M}} \Phi \bar{d}_R H^\dagger \ell_L + h.c. \quad (29)$$

give rise to the desired couplings

$$\lambda_u = \hat{\lambda}_u \frac{v}{\mathcal{M}}, \quad \lambda_d = \hat{\lambda}_d \frac{v}{\mathcal{M}}, \quad (30)$$

after the Higgs field acquires its VEV, $\langle H \rangle = (0, v)^T$. Equation (29) determines the $SU(3) \otimes SU(2) \otimes U(1)$ quantum numbers of the scalar leptoquark field Φ to be the same as those of the right-handed up quark.

Appropriate values of λ_u and λ_d are achieved when the mass scale \mathcal{M} of the effective interaction is below about 10 TeV. This scale is low enough to require some further discussion about the underlying dynamics. In the context of perturbative physics, it is possible to generate the effective Lagrangian in eq. (29) via exchange of a single non-chiral fermion X with the same quantum numbers of the left-handed quark doublet, and with the following interactions:

$$\mathcal{L} = \left[y_\ell \Phi \bar{X}_R \ell_L + y_u \bar{u}_R H^T (-i\sigma_2) X_L + y_d \bar{d}_R H^\dagger X_L + h.c. \right] - \mathcal{M} \bar{X} X . \quad (31)$$

After integrating out the heavy field X , we recover eq. (29) with $\hat{\lambda}_{u,d} = y_\ell y_{u,d}$. We have no satisfactory explanation for why the field X couples only to first generation quarks and leptons. This model is just meant to give an illustrative example of a possible leptoquark which can produce CC events at HERA.

The interactions in eq. (31) generate, after electroweak symmetry breaking, a mass mixing between ordinary quarks and the field X . Keeping just the leading effects in $1/\mathcal{M}$, the mixing is only among right-handed particles and it induces a coupling of the W boson with the first-generation hadronic right-handed current, suppressed by a factor $\rho \equiv (\lambda_u \lambda_d) / y_e^2$ with respect

to the usual left-handed current. Direct limits on hadronic right-handed currents from deep-inelastic scattering experiments give $\rho^2 < 0.009$ at 90% CL [20]. Neutral currents coupled to the Z boson are also modified in their isospin part J_3^μ , but of course not in their electromagnetic part. The vector and axial-vector couplings of a first generation quark f become

$$v_f = T_f \left(1 + \frac{\lambda_f^2}{y_e^2} \right) - 2Q_f \sin^2 \theta_W, \quad a_f = T_f \left(1 - \frac{\lambda_f^2}{y_e^2} \right), \quad (32)$$

where T_f and Q_f are the third-component isospin and electric charge of the fermion f . APV experiments constrain the new contributions in eq. (32). Comparing the measured and predicted values of the cesium “weak charge”, $Q_W^{exp} = -72.11 \pm 0.93$ [12], $Q_W^{SM} = -73.2 \pm 0.2$ [13], we obtain an allowed range for λ_u and λ_d given at 90% CL by

$$-1.3 \times 10^{-2} < \left(\frac{\lambda_d}{y_e} \right)^2 - 0.89 \left(\frac{\lambda_u}{y_e} \right)^2 < 2.2 \times 10^{-3}. \quad (33)$$

Using $|\lambda_d| \simeq 4 \times 10^{-2} / \sqrt{1 - \mathcal{B}_{\nu u}}$, we find that eq. (33) allows values of $\mathcal{B}_{\nu u}$ as large as 77%, for $y_e \sim 1$. Precision measurements at LEP do not constrain the model further, and therefore the possibility of CC events at HERA from this particular leptoquark with non-gauge-invariant effective couplings is still allowed.

Another viable alternative is a leptoquark which couples simultaneously to the $\bar{e}_R^{(1)} q_L^{(1)}$ and $\bar{\ell}_L^{(i)} u_R^{(2)}$ currents ($i = 1, 2, 3$). Here we have specified the generation indices of the different fields. If CC events were observed at HERA and such a leptoquark was responsible for them, we expect the striking signature of leptonic D decays with rates much larger than in the SM if $SU(2) \otimes U(1)$ is respected:

$$BR(D^0 \rightarrow e^{\pm(1)} e^{\mp(i)}) \simeq 1 \times 10^{-6} \frac{\mathcal{B}_{\nu c}}{(1 - \mathcal{B}_{\nu c})^3} \left(\frac{200 \text{ GeV}}{M} \right)^4 \quad i = 1, 2. \quad (34)$$

The present experimental limits $BR(D^0 \rightarrow e^\pm e^\mp) < 1.3 \times 10^{-5}$ and $BR(D^0 \rightarrow e^\pm \mu^\mp) < 1.9 \times 10^{-5}$ [14] allow large values of the leptoquark branching ratio into $\bar{\nu}c$, $\mathcal{B}_{\nu c}$. The leptoquark under consideration belongs to an $SU(2)$ doublet and the mass of its partner is constrained by the electroweak ρ parameter. Allowing for a new physics contribution $\Delta\rho < 1 \times 10^{-3}$, we find that the second leptoquark must be lighter than 250 GeV. This state has electric charge $5/3$, gives rise only to NC events and it is produced by positron scattering off up quarks. Its cross section is, in the worst case (for $M = 250$ GeV), only 4 or 5 times smaller than the cross section of its weak partner, allegedly produced at HERA.

Let us consider the production of a leptoquark resonance from sea quarks. Production from \bar{u} or \bar{d} quarks in the sea is excluded [3, 6] by the e^-p HERA data. In the case of a leptoquark produced in the e^+s channel, the existence of a $\bar{\nu}u$ final state is severely constrained by $e - \mu$ universality in $K \rightarrow \ell \nu$ [21]. On the other hand, the possibility of a $\bar{\nu}c$ final state is still allowed. This leads to a remarkable signature in leptonic D_s decays

$$BR(D_s^- \rightarrow e^- \bar{\nu}) \simeq 6 \times 10^{-3} \frac{\mathcal{B}_{\nu c}}{(1 - \mathcal{B}_{\nu c})^3} \left(\frac{200 \text{ GeV}}{M} \right)^4 \quad i = 1, 2. \quad (35)$$

We are not aware of any existing experimental limit on this quantity.

To conclude, we recall that a leptoquark with branching ratio equal to 1 in e^+q is practically excluded by the Tevatron, as discussed in more detail in the next section. Therefore on one hand some branching fraction in the CC channel is needed. On the other hand, we find that there is limited space for the possibility that a leptoquark can generate a CC signal at HERA with one single parton quark in the final state. This occurrence would indicate $SU(2) \otimes U(1)$ violating couplings and corresponding higher dimension effective operators with Higgs fields, or couplings to a current containing the charm quark.

4 Squarks with R-Parity Violating Decays

4.1 General Constraints

Perhaps the most attractive possibility is that the HERA signal is a manifestation of supersymmetry [22], in the specific form of a squark with an R-violating coupling [23]. Production of squarks at HERA via R -violating interactions has been an area of active study for quite some time (see, e.g., refs. [24, 25, 26].) Recently this possibility has been reconsidered in detail [3, 4, 6] in the light of the new HERA findings. The R-violating coupling is of the form $\lambda'_{ijk} L_1 Q_j D_k^c$ and, given the present experimental limits on such interactions, the possible production channels are $e^+d \rightarrow \tilde{c}_L$, $e^+d \rightarrow \tilde{t}_L$, and with more marginal chances, $e^+s \rightarrow \tilde{t}_L$ [3]. Such squarks are very particular leptoquarks and, in fact, their decay into the final state $\bar{\nu}u$ is not allowed. However, it has been shown that in all cases R-conserving decay channels could have competing branching ratios with the R-violating ones [3]. This fact not only makes the squark option more easily compatible with the Tevatron bounds, but also offers the possibility of inducing a CC signal arising from some special R-conserving decay channels.

Before starting the discussion of the possible decay chains, we first introduce some notation and discuss current constraints on these scenarios. We denote by \mathcal{B}_{eq} the branching ratio for the R-violating e^+q decay mode, and $\mathcal{B}_R = 1 - \mathcal{B}_{eq}$ the branching ratio into the R-conserving ones. We also define $\lambda_0^q = \lambda'_{1iq} \cdot \sqrt{\mathcal{B}_{eq}}$ to be the variable whose strength is directly measured by the NC event rate. We recall that fits to the H1 and ZEUS data give [3] $\lambda_0^d = 0.04$ (production on d quarks), and $\lambda_0^s = 0.3$ (production on s quarks). These estimates are clearly affected by the statistical uncertainty on the observed signal, as well as by uncertainties in the theoretical calculation of the production cross section. Recent calculations of NLO corrections to the leptoquark cross section at HERA [27] show a K -factor correction of the order of 30% relative to the Born evaluation used in ref. [3], and a residual uncertainty due to scale variations of the order of $\pm 10\%$. Accounting for these effects and for the statistical uncertainty of the observed signal, we shall consider values of λ_0^d (λ_0^s) in the range $0.03 - 0.04$ ($0.2 - 0.3$).

It is important to notice that, even in absence of constraints from CC events, improved data from the Tevatron [19] on one side and from APV [12] on the other considerably reduce the window for the explanation based on $e^+d \rightarrow \tilde{c}$ or \tilde{t} (and, more in general, for all leptoquarks). Consistency with the Tevatron demands a value of \mathcal{B}_{eq} smaller than 1. In fact, the most recent NLO estimates of the squark and leptoquark production cross sections [28, 29] allow to estimate that at 200 GeV approximately 6–7 events with e^+e^-jj final states should be present in the

combined CDF and D0 data sets. The absence of event candidates should allow to exclude a value of $\mathcal{B}_{eq}^2 \gtrsim 0.5$ at 95%CL. This constraint could even be tighter, considering that a gluino with mass not much larger than the squark mass would further increase the squark production rate. To be conservative, we shall in any case demand $\mathcal{B}_{eq} \lesssim 0.75$. As for the lower limit on \mathcal{B}_{eq} , the new experimental result on APV in cesium quoted in the previous section and the relation

$$\Delta C_{1d} = + \frac{(\lambda'_{1id})^2 \sqrt{2}}{8m_{\tilde{q}_i}^2 G_F} \quad (36)$$

(with C_{1d} defined in ref. [14], p.87), lead to the bound

$$|\lambda'_{1id}| < 0.055 \left(\frac{m_{\tilde{q}_i}}{200 \text{ GeV}} \right) \quad (37)$$

at 90%CL. In turn, using the relation $|\lambda'_{1id}| = (0.03 - 0.04)/\sqrt{\mathcal{B}_{eq}}$, this translates into $\mathcal{B}_{eq} \gtrsim 0.3 - 0.5$. Thus, on rather general grounds only the narrow window $0.3 \sim 0.5 \lesssim \mathcal{B}_{eq} \lesssim 0.75$ is left.

We come now to the study of the decay processes. We recall first that the required balance of R-violating and R-conserving decay channels can be obtained if we assume that the mode $\tilde{c} \rightarrow s\chi^+$ is forbidden by phase space, that is $m_{\chi^+} > 200 \text{ GeV}$, while the channel $\tilde{c} \rightarrow c\chi_1^0$ is allowed and suitable values of the relevant parameters are selected. In the case of the stop decays, we observe that the $t\chi^0$ mode is closed, due to the large top mass. The $b\chi^+$ mode can naturally compete with the R-violating one for a large range of chargino masses if the production involves an s quark, as in this case λ' has a strength of the order of the EW coupling. For production on a d quark λ' is very small, and the chargino mass needs to be fine tuned in order to have a sufficient phase-space suppression of the otherwise large R-conserving decay width.

In the case of \tilde{c} production, the most promising decay mode for a CC signal is the chain⁴:

$$\tilde{c} \rightarrow c\chi^0 \rightarrow c\nu_e \tilde{\nu}_e \rightarrow c\nu_e q\bar{q}' , \quad (38)$$

where in the last step the R-violating coupling is involved. The $\nu\tilde{\nu}$ decay of the neutralino competes with the analogous decay into $\ell\tilde{\ell}$. In order to maximize the CC decay mode, we assume a large mass for all right components of the charged sleptons. Furthermore, we shall assume for simplicity all sneutrino species to be degenerate, and the standard $SU(2)$ relation between the masses of the left components of charged sleptons and of sneutrinos:

$$m_{\tilde{\ell}_L}^2 = m_{\tilde{\nu}_\ell}^2 + |\cos 2\beta| m_W^2 . \quad (39)$$

The relative branching ratios into the neutral and charged slepton channels are given by:

$$\frac{BR(\chi_i^0 \rightarrow \ell\tilde{\ell}_L)}{BR(\chi_i^0 \rightarrow \nu_\ell \tilde{\nu}_\ell)} = \frac{(\tan \theta_W N_{i1} + N_{i2})^2}{(\tan \theta_W N_{i1} - N_{i2})^2} \left(\frac{m_{\chi_i^0}^2 - m_{\tilde{\ell}}^2}{m_{\chi_i^0}^2 - m_{\tilde{\nu}_\ell}^2} \right)^2 , \quad (40)$$

⁴While our study was performed by considering decays to all possible χ_i^0 states ($i = 1, \dots, 4$), it turns out that only decays to the lightest neutralino are relevant and evade the overall constraints set by the request of a sizeable CC signal.

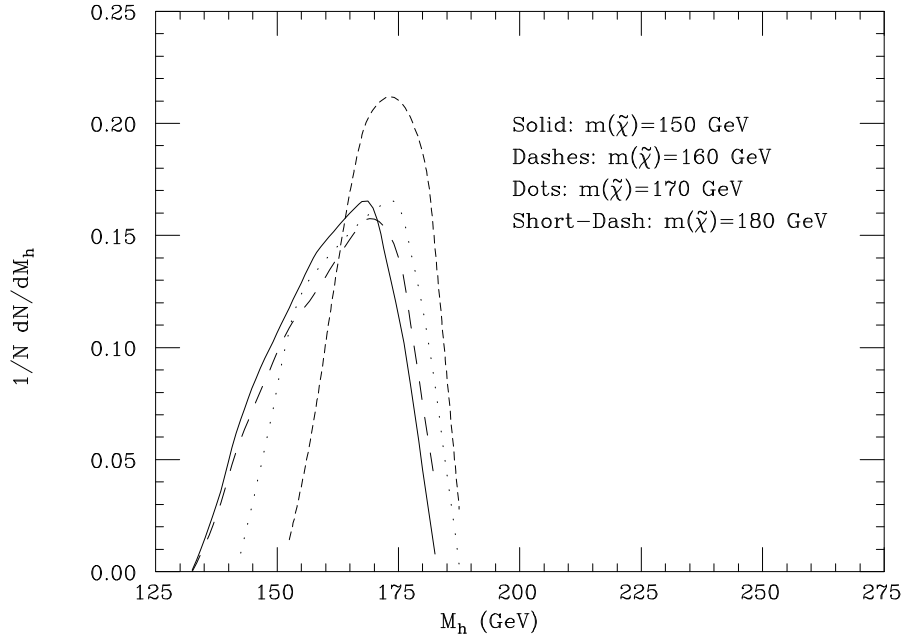


Figure 1: *Distribution of the mass variable M_h [1, 2, 30] for the CC decay $\tilde{c} \rightarrow c\nu q\bar{q}$, for $m_{\tilde{\nu}} = 60$ GeV and different values of m_{χ^0} .*

where i is the label of the neutralino produced in the \tilde{c} decay, and N_{ij} are the elements of the unitary matrix that diagonalizes the neutralino mass matrix in the $SU(2) \otimes U(1)$ gaugino basis [22]. The dependence of this ratio on the MSSM parameters will be studied in the following. The decays of second and third generation sneutrinos are dominated by the nearby pole of the virtual $\tilde{\nu}_e$, $\tilde{\nu}_i \rightarrow \nu_i \nu_e \tilde{\nu}_e$, and give rise to a signature kinematically similar to that of the direct $\chi^0 \rightarrow \nu_e \tilde{\nu}_e$ mode.

In the case of \tilde{t} production, the most promising decay mode for a CC signal is driven by the chain:

$$\tilde{t} \rightarrow b\chi^\pm \rightarrow b\nu_\ell \tilde{\ell}_L, \quad (41)$$

followed by one of the possible decays of the charged slepton into $\tilde{\nu}_e$. There is a competing (NC) decay of the χ^\pm : $\chi^\pm \rightarrow \ell \tilde{\nu}_\ell$. The relative branching ratios of the two modes are given by:

$$\frac{BR(\chi_i^\pm \rightarrow \ell \tilde{\nu}_\ell)}{BR(\chi_i^\pm \rightarrow \nu_\ell \tilde{\ell}_L)} = \frac{|U_{i1}|^2}{|V_{i1}|^2} \left(\frac{m_{\chi_i^\pm}^2 - m_\ell^2}{m_{\chi_i^\pm}^2 - m_{\tilde{\nu}_\ell}^2} \right)^2, \quad (42)$$

where i is the label of the chargino produced in the \tilde{t} decay, and U_{ij} , V_{ij} are the elements of the matrices that diagonalize the chargino mass matrix [22]. For $\tan\beta = 1$ the two decay rates are equal. For $\tan\beta > 1$ the $e\tilde{\nu}$ mode is always favoured. As we shall see in the following, independent reasons will select the region of $\tan\beta \sim 1$ as the most favourable one. In these conditions, it is possible to verify that the dominant decay mode of the $\tilde{\ell}_L$ is the one mediated

by a virtual W , and leads to $\tilde{\ell}_L \rightarrow \tilde{\nu}_\ell f \bar{f}'$, with f, f' an $SU(2)$ fermion doublet. The close mass degeneracy between $\tilde{\ell}_L$ and $\tilde{\nu}$, due to low $\tan\beta$, makes the overall transition $\tilde{\ell}_L \rightarrow \tilde{\nu}_e + X$ almost a “1-body” decay, with the unstable $\tilde{\nu}_e$ carrying away most of the $\tilde{\ell}$ energy. The overall topology of the final state will therefore appear very close to that of the $\tilde{c} \rightarrow c \nu \tilde{\nu}$ decay. For this reason we shall concentrate in the following on the kinematical properties of the \tilde{c} decays, since the CC decays of the stop share the same overall features.

4.2 Constraints on the \tilde{c} case

We now move on to discuss the constraints on the supersymmetric particle spectrum dictated by the kinematical features of the possible CC candidates reported by H1 [1]. The first constraints come from the reconstructed mass spectrum of the four CC high- Q^2 candidates. The presence of massive intermediate states in the decay of the scalar quark significantly softens and smears out the mass of the resonance, which can be reconstructed using the Jacquet–Blondel variable M_h [30]:

$$M_h = \sqrt{\frac{Q_h^2}{y_h}}, \quad Q_h^2 = \frac{P_{T,h}^2}{1 - y_h}, \quad y_h = \frac{\sum(E - P_z)}{2E_e^0}, \quad (43)$$

where E_e^0 is the energy of the positron beam, and the sum extends over all detectable energy in the final state. For the sake of definiteness, we shall now concentrate on the case of production and decay of the \tilde{c} . In the \tilde{c} case, the M_h [1, 2, 30] distribution of the CC final states depends on the value of the neutralino and of the sneutrino masses. We show the dependence on the neutralino mass in fig. 1, where we fixed $m_{\tilde{\nu}} = 60$ GeV. The distributions, normalized to unit area, were obtained by applying the H1 selection cuts $E_T > 50$ GeV and $Q^2 > 15000$ GeV². Higher values of the sneutrino mass will soften each individual distribution. Lower values of the sneutrino mass are excluded by the current LEP2 data, as will be shown in the following.

Comparing these distributions with the H1 data (see table 7 of ref. [1]), and taking into account the quoted 10% relative uncertainty on the measured M_h , we conclude that only neutralino masses in excess of 170–180 GeV have a chance of producing the observed signals.

Additional information of the spectrum comes from the study of the topology of the final-state hadronic system. With such a large neutralino mass, the charm jet produced in the \tilde{c} decay would be very soft and broad. The most energetic hadronic activity in the event would come from the R -parity violating two-quark decay of the sneutrino. A light sneutrino could result in the two jets being merged into a single broad one, while a heavy sneutrino would result in two widely separated jets. These alternatives are illustrated in fig. 2, where we plot the distribution of the $\eta - \phi$ separation (δR) between the two highest- E_T partons in the events. As the figure shows, experimental evidence for a hadronic final state mostly consisting of a single broad jet would require a sneutrino mass as light as possible and not exceeding 70 GeV.

Similar conclusions can be reached by a study of the event rate. The fraction of events which satisfies the H1 selection cuts is plotted in fig. 3, as a function of the sneutrino mass and for different choices of the neutralino mass. Once again, acceptable efficiencies can be obtained only assuming a large neutralino mass and a small sneutrino mass.

We now proceed to verifying whether these kinematical constraints allow for acceptable branching ratios into the desired CC final states. Figure 4 shows, as a function of the neutralino

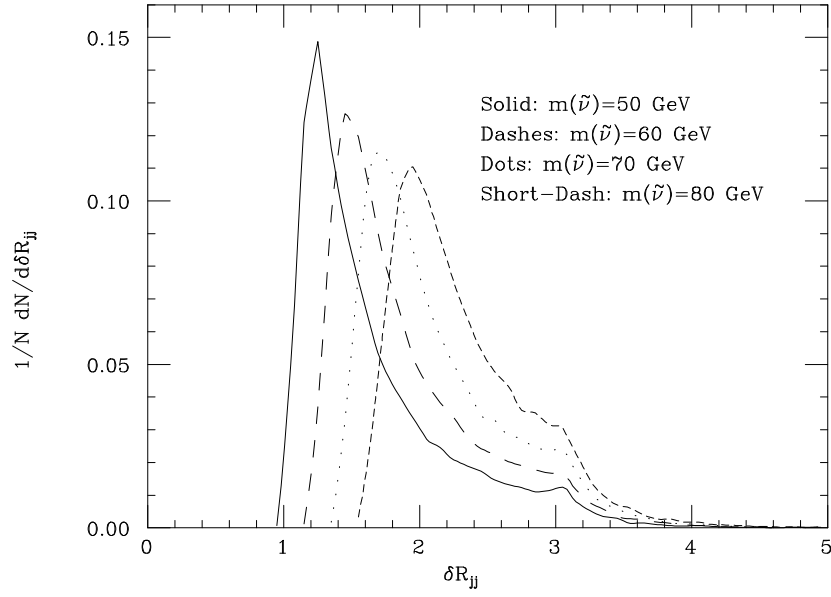


Figure 2: *Spatial separation of the two leading quarks from the $\tilde{c} \rightarrow cvq\bar{q}$ decay, for $m_{\chi^0} = 180$ GeV and with various sneutrino masses.*

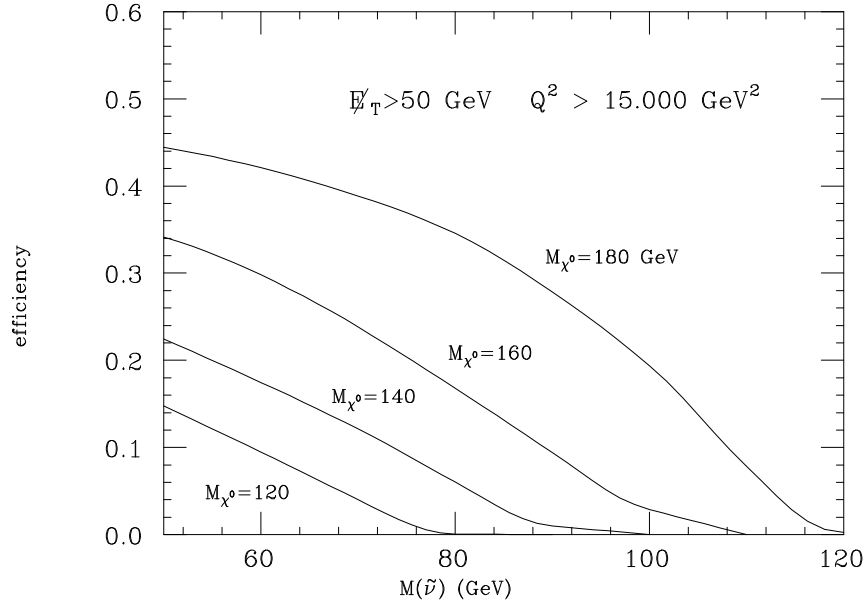


Figure 3: *Charged current decay efficiencies.*

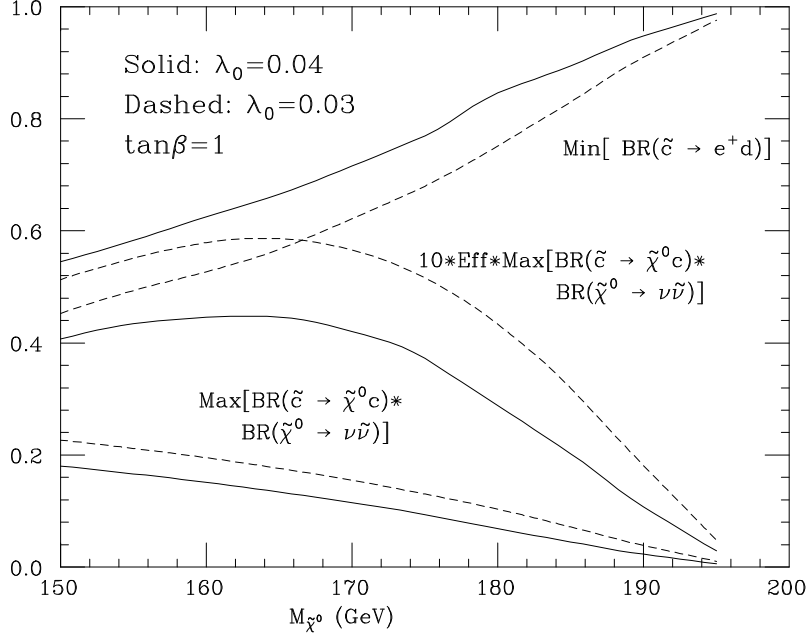


Figure 4: Decay branching ratios of relevance to the CC \tilde{c} decay, as a function of the neutralino mass. The uppermost curves correspond to the lowest possible value of \mathcal{B}_{eq} consistent with $m_{\tilde{\chi}^\pm} > 200$ GeV and $\tan\beta = 1$. The lowest set of curves gives the maximum combined branching ratio for the CC \tilde{c} decay, under the same assumptions. The central set of curves gives the product of the kinematic efficiency (shown in fig. 3) times the overall CC branching ratio, rescaled by a factor of 10.

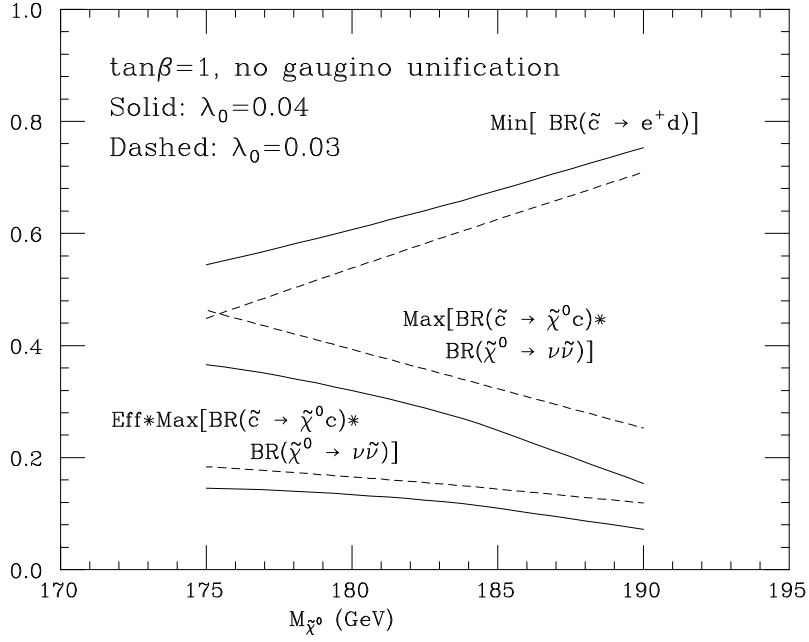


Figure 5: *Decay branching ratios of relevance to the CC \tilde{c} decay, as a function of the neutralino mass, in absence of the gaugino-mass unification hypothesis. The upper curves correspond to the lowest possible value of \mathcal{B}_{eq} consistent with $m_{\chi^\pm} > 200$ GeV and $\tan\beta = 1$. The central set of curves gives the maximum combined branching ratio for the CC \tilde{c} decay, under the same assumptions. The lowest set of curves gives the product of the kinematic efficiency (shown in fig. 3) times the overall CC branching ratio.*

mass and for $\tan\beta = 1$, the minimum value of the branching ratio for the NC decay $\tilde{c} \rightarrow e^+ d$ allowed by scanning the (μ, M_2) plane under the assumption of gaugino mass unification and that the mass of the lightest chargino be larger than 200 GeV. We present two curves, corresponding to the choices of the coupling $\lambda' \sqrt{\mathcal{B}_{ed}} \equiv \lambda_0^d = 0.03$ and 0.04. The constraint $\mathcal{B}_{ed} < 0.75$ excludes neutralino masses larger than approximately 180 GeV. As a result we see that the neutralino mass value is fixed to be in the range 170–180 GeV, the lower limit being dictated by the kinematics, and the upper limit being defined by the branching ratio requirements. The APV constraint $\mathcal{B}_{eq} > 0.5$ is automatically satisfied in the neutralino mass range $m_{\chi^0} > 170$ GeV, as fig. 4 shows.

The previous results were obtained using $\tan\beta = 1$. Similar results can be obtained increasing the value of $\tan\beta$. The maximization of the rate would select neutralinos with a higher bino content.

If we take into account the possible alternative neutralino decay mode, $\chi^0 \rightarrow \ell\tilde{\ell}$, and assume the mass degeneracy of $\tilde{\ell}_L$ and $\tilde{\nu}_L$ resulting from $\tan\beta = 1$ and $SU(2) \otimes U(1)$ invariance, a scan of the (μ, M_2) plane leads to the upper value of the combined branching ratios $\mathcal{B}(\tilde{c} \rightarrow c\chi^0) \times \mathcal{B}(\chi^0 \rightarrow \nu\tilde{\nu})$ given in fig. 4. The maximum attainable values for such branching ratio

are around 15% in the relevant neutralino mass range. Combined with the efficiency of the selection cuts, this results in an overall fraction of detectable CC events of about 5%, assuming a sneutrino of 60 GeV, namely as light as currently allowed by LEP2. This should be compared to a combined efficiency (64%) times branching ratio (70%) for the NC \tilde{c} final states of about 45%. The predicted relative rate of CC over NC events is therefore of the order of 1/9. This low ratio would predict only a fraction of a CC event in the current data sample, and it would require a significant statistical fluctuation in the observed rates for this scenario to be tenable.

A more optimistic conclusion could be reached by relaxing some of the underlying MSSM assumptions. For example, one could remove the constraint of gaugino-mass unification. The situation in this case is shown in fig. 5, where we plot the maximum possible CC branching ratio obtained by scanning the parameters (μ, M_1, M_2) with the $m_{\chi^\pm} > 200$ GeV constraint. The optimal condition is reached when the gaugino mass parameters M_1 and M_2 are comparable in size. Notice that in this case one can benefit from both a larger $BR(\tilde{c} \rightarrow c\chi^0)$, and from a $BR(\chi^0 \rightarrow \nu\tilde{\nu})$ close to 1. The relative rate CC/NC can attain values as large as 1/3, consistent with the reported CC excess. We point out that in this case the interesting signature of same-sign dileptons at the Tevatron, typical of conventional R-conserving decays, would be significantly suppressed.

We point out once more that for this scenario to have any chance of working, a sneutrino mass just above the current LEP2 constraints is required, and its discovery at the coming high-statistics $\sqrt{s} = 185$ GeV run of LEP2 should be granted. For illustration, we show in fig. 6 the sneutrino e^+e^- production cross section at $\sqrt{s} = 172$ and 185 GeV, obtained by assuming the constraints on the values of μ and M_2 set by the previous analyses. For reference, the current cross section limit on 4-jet final states from the decay of a pair of resonances in the mass range 50–60 GeV is about 0.5 pb [32]. Notice however that Aleph [33] sees a 4-jet signal above background, which in principle could be explained by pair production of $\tilde{\nu}_e$ followed by $\tilde{\nu} \rightarrow jj$.

4.3 Constraints on the \tilde{t} case

The kinematical constraints on the final states of \tilde{t} production are analogous to those studied in the case of \tilde{c} production and decay. In particular, even in this case it is important that the chargino mass be as large as possible, compatibly with an acceptable value of \mathcal{B}_{eq} . The value of \mathcal{B}_{eq} for \tilde{t} decays is plotted in fig. 7 as a function of the chargino mass. The kinematical constraint on the allowed range of gaugino masses is consistent with the requirements set by the branching ratios in the case of the R -violating coupling of the \tilde{t} to e^+d . In particular, chargino masses in the range of 180 – 190 GeV are acceptable. The inclusion of mixing in the $\tilde{t}_L - \tilde{t}_R$ system, which leaves unaltered both the kinematics and the combined Tevatron and APV constraints on \mathcal{B}_{eq} , modifies this range only marginally. In the case of coupling to e^+s , the Tevatron limits exclude the reference value of $\lambda_0^s = 0.3$, and allow chargino masses up to 175 GeV for $\lambda_0^s = 0.2$.

As already discussed, the CC final state for \tilde{t} decay is obtained via the transition $\tilde{t} \rightarrow b\chi^\pm$, followed by $\chi^\pm \rightarrow \nu\tilde{\ell}^\pm$. As already remarked, large efficiencies and an M_h spectrum consistent with that of the potential H1 candidates require a slepton as light as possible. This forces the selectron mass not to exceed significantly the value of 60 GeV. Given the LEP2 limit on

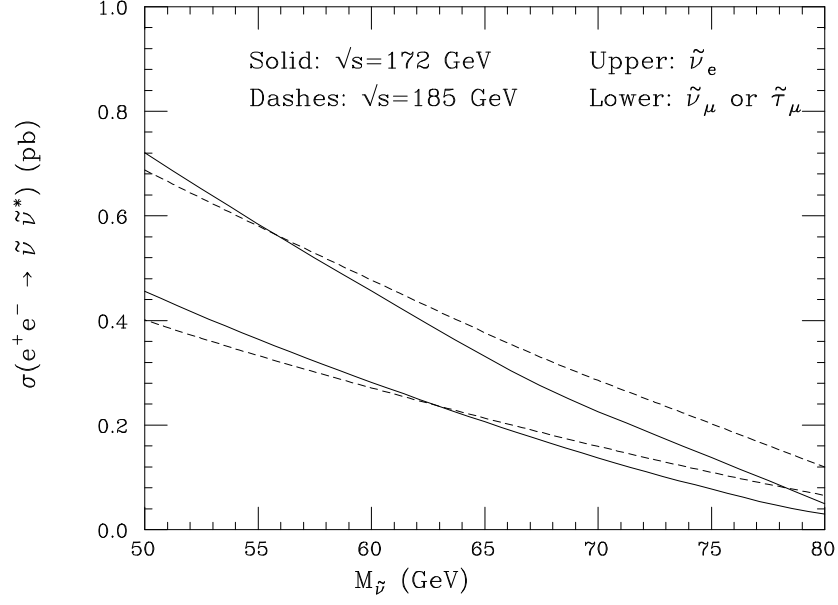


Figure 6: Sneutrino cross section at $\sqrt{s} = 172$ and 185 GeV. The $\tilde{\nu}_\mu$ cross section is independent of supersymmetric parameters, and is clearly equal to the $\tilde{\nu}_\tau$ cross section. For the $\tilde{\nu}_e$ cross section we chose $\tan\beta = 1$ and the (μ, M_2) values which maximise the overall \tilde{c} CC decay rate. ISR corrections are included [31].

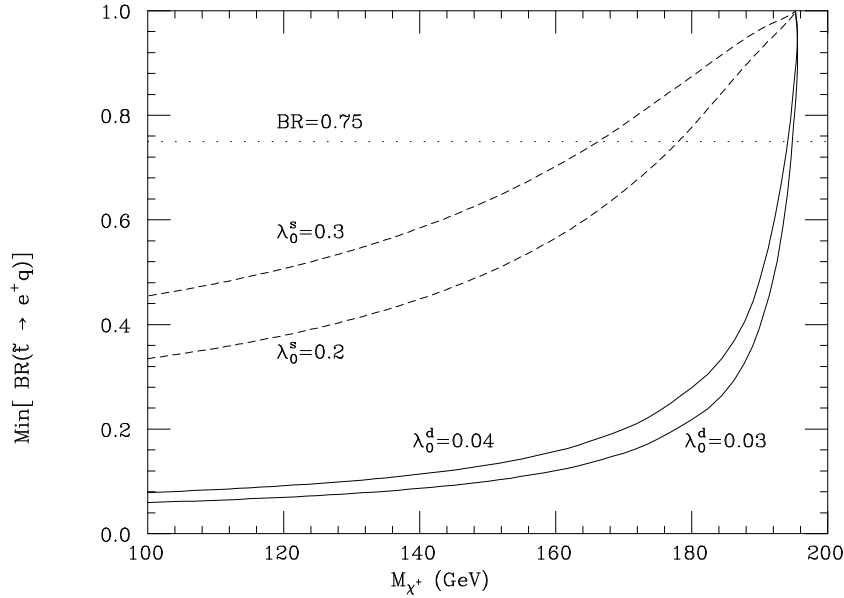


Figure 7: *Minimum $\tilde{t} \rightarrow e^+q$ branching ratios, as a function of the chargino mass and of the R -violating coupling strength λ_0^q , for $\tan\beta = 1$. The branching ratios are minimised for a gaugino-like chargino.*

the sneutrino mass, which is also at the level of 60 GeV, we conclude from eq. (39) that $\tan\beta$ should be very close to 1.

A chargino mass of about 190 GeV allows, in the case of coupling to the d quark, values of \mathcal{B}_{eq} as low as 50%, which is the limit permitted by the APV constraints. Assuming a 50% branching ratio for the $\chi^+ \rightarrow \nu\bar{\ell}^+$ decay (consistent with the assumption of $\tan\beta$ close to 1), and using a typical kinematical efficiency of 50%, we obtain an overall fraction of 12% CC final states passing the H1 cuts. This can be compared to the $64\%(\text{efficiency}) \times 50\%(\text{branching ratio}) = 32\%$ fraction of predicted NC events. The relative CC/NC rate can therefore be as large as $1/3$, which is well consistent with the H1 indications.

5 Conclusions

Even in absence of additional constraints from the CC channel, it is not easy to incorporate the possible indications of new physics from HERA in our present theoretical understanding. For example, contact terms require values of $g^2/\Lambda^2 \sim 4\pi/(3 \text{ TeV})^2$, which would imply a very strong nearby interaction. Indeed for g^2 of the order of the $SU(3) \otimes SU(2) \otimes U(1)$ couplings, Λ would fall below 1 TeV, where the contact term description is inadequate. Squarks with R -parity violation are perhaps the most appealing version of leptoquarks. However they require a very peculiar family and flavour structure, whose pattern can be embedded [34] in a grand unification framework. The already intricate problem of the mysterious texture of masses and

couplings is however terribly enhanced in these scenarios.

If CC events are observed in the same range of Q^2 at HERA at a roughly comparable rate, then most of the models so far considered for the interpretation of NC events are to be reconsidered. For example, we could not find an acceptable set of contact terms compatible with $SU(2) \otimes U(1)$ invariance. In the case of leptoquarks, only peculiar models with $SU(2) \otimes U(1)$ breaking couplings or with charged currents involving the c quark survive. The CC events show in this case only one-parton jets in the final state and the branching ratio for CC decays could well be of the order of 50%.

Squarks could produce CC events with multi-parton final states. Clean one-jet final states, as observed in the NC events, would therefore require neutralinos (in the \tilde{c} case) or charginos (in the \tilde{t} case) with a mass very close to 200 GeV, and sleptons as light as possible. The additional constraints set by the Tevatron and APV limits on the branching ratios limit the neutralino mass to the range 170 – 180 GeV. If the gaugino-unification relation holds, at best one can hope for the relative rate of CC to NC events to be around 1/9. Relaxing the gaugino-mass unification hypothesis allows this ratio to increase to the acceptable value of 1/3.

Similar kinematic constraints exist in the case of the \tilde{t} . In this case, one is also forced to assume the \tilde{e}_L mass to be as light as possible, forcing the value of $\tan\beta$ to be around 1. Acceptable values of the chargino mass are in the range of 180 – 190 GeV, if one assumes the $e^+d \rightarrow \tilde{t}$ production mechanism. The $e^+s \rightarrow \tilde{t}$ case leads instead to lower values of the chargino mass, which are not obviously consistent with the M_h spectrum of the H1 CC candidate events. The CC/NC ratio can be as large as 1/3. In all cases, one is left with the prediction that the sneutrino (and possibly the left selectron as well) should be within the reach of the coming LEP2 runs.

We look forward to the results of the ongoing run of HERA, that will hopefully clarify to some extent the present situation.

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